COMPARATIVE INVESTIGATION ON USING CRYOGENIC MACHINING IN CNC MILLING OF TI-6AL-4V TITANIUM ALLOY

(Cryogenic end milling of titanium alloy)

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ABSTRACT

Ti-6Al-4V titanium alloy is one of the most important materials in industry, 80% of which is used in aerospace industry. Titanium alloys are also notoriously difficult-to-machine materials owing to their unique material properties imposing a major bottleneck in manufacturing systems. Cryogenic cooling has been acknowledged as an alternative technique in machining to improve the machinability of different materials. Although milling is considered to be the major machining operation for the manufacture of titanium components in aerospace industries, studies in cryogenic machining of titanium alloys are predominantly concentrated on turning operations. To address this gap, this article provides an investigation on the viability of cryogenic cooling in CNC end-milling of aerospace-grade Ti-6Al-4V alloy using liquid nitrogen in comparison with traditional machining environments. A series of machining experiments were conducted and surface roughness, tool life, power consumption, and specific machining energy were investigated for cryogenic milling as opposed to conventional dry and flood cooling. Analysis revealed that cryogenic machining using liquid nitrogen has the potential to significantly improve the machinability of Ti-6Al-4V alloy in CNC end-milling using solid carbide cutting tools and result in a paradigm shift in machining of titanium products. The analysis demonstrated that cryogenic cooling has resulted in almost three times increased tool life and the surface roughness was reduced by 40% in comparison with flood cooling.

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INTRODUCTION

Titanium alloys are widely used throughout many industrial sectors such as aerospace and medical where weight, thermal stability, material strength, hardness and/or biocompatibility are of primary concern (Ulutan and Ozel, 2011). Ti-6Al-4V, an α-β variant of titanium alloys is the most used type of titanium alloys across various industries forming 50% of the global titanium metal production, 80% of which is used in aerospace and medical industries (Boyer et al., 1994, Lütjering and Williams, 2007).

Titanium alloys are also notorious for their poor machinability owing in part to their superior material characteristics (Davim, 2014). Titanium alloys possesses the highest strength to weight ratio among all structural materials with very high hardness and toughness which results in high machining temperatures. It is reported that poor thermal conductivity of titanium alloys results in localised temperatures in excess of 1000°C at the tool tip leading to high thermal gradient leading to welding, diffusion and reduction in cutting tools' hardness (Pramanik, 2014, Ezugwu, 2005). These, together with high strain hardening tendency of titanium are known as the major sources of premature tool failure in machining titanium alloys (Davim, 2014). Generous use of cutting fluids at high pressures is one of the common techniques to improve machinability of titanium alloys. The cutting fluid is used to lubricate the cutting zone and reduce the cutting temperature. However, cutting fluids are identified as environmental and health hazardous substances and increasing governmental regulations for use, maintenance and disposal of cutting fluids have resulted in increased costs associated with the use of cutting fluids.

Cryogenic cooling using liquefied gases, with liquid nitrogen (LN_2) being the most used cryogen, has attracted many researchers as an environmentally friendly alternative to conventional cutting fluids. Kaynak et al. (2014) identified cryogenic cooling as the most favourable machining environment as opposed to dry, flood and minimum quantity lubricant (MQL) in order to improve surface integrity in machining operations.

Hong and Zhao (1999) examined the material properties of Ti-6Al-4V alloy at various temperatures. Based on their findings, Ti-6Al-4V maintains a significant portion of its toughness at cryogenic temperatures whilst its tensile strength and toughness increases significantly. Therefore, it has been found that freezing the workpiece material is not beneficial for machining titanium alloys suggesting to spray a small amount of LN_2 into the cutting zone (Hong and Zhao, 1999). Bordin et al. (2015) identified dry and cryogenic machining as most suitable methods for machining titanium parts for medical parts as it minimises the requirements for further cleaning after machining. As a result of their experimental studies, the authors identified that cryogenic cooling can significantly minimise adhesion wear in turning of additively manufactured Ti-6Al-4V titanium parts. Deix et al. (2014) developed an analytical model based on finite element analysis (FEA) and found that cryogenic cooling can significantly reduce the cutting temperature resulting in decreased tool wear as compared to dry machining. On the other hand, cryogenic cooling has produced higher torque and axial force than dry machining.

Ambrosy et al. (2014) conducted a series of experimental investigations on turning AISI 4140 steel. The researchers found that both tool nose radius and machining environment affect the surface roughness. In their studies, cryogenic cooling has resulted in increased Ra and Rz surface roughness as compared to dry machining.

Rotella et al. (2014) studied the effect of different machining environments, namely dry, MQL and cryogenic cooling on surface integrity of Ti-6Al-4V in turning operations at various cutting speeds and feed rates. The researchers found that the lowest surface roughness was produced in cryogenic environment. Furthermore, they noticed that cryogenic cooling improves dynamic recrystallisation and prevents grain growth within the material whilst increasing the surface and subsurface microhardness of the machined material.

Strano et al. (2013) empirically studied the effects of cryogenic cooling on cutting forces and tool wear in CNC turning of Ti-6Al-4V using a multilayer TiAlN-AlCrO coated tungsten carbide tool. They (Strano et al., 2013) reported that cryogenic cooling reduced the growth rate of flank wear resulting in 38.8% increased tool life as compared to flood cooling. Furthermore, the study revealed that cryogenic cooling reduced various components of cutting forces by 4% to11% in comparison with flood cooling. Cryogenic cooling has also been acknowledged as a method for reducing the tool wear rate in machining NiTi shape memory alloys (Kaynak et al., 2013). Kaynak et al. (2013), studied the effect of machining environment and cutting speed in turning NiTi alloy. In their study, tool life was deteriorated by increasing cutting speed where notch wear at the depth of cut was dominant in all tested machining environments of cryogenic, dry and MQL. Cryogenic cooling has favourably reduced cutting temperature resulted in an extended tool life. Raza et al. (2014) studied the effects of a range of machining environments namely, dry, chilled air, MQL, cooled MQL, flood and cryogenic cooling in turning Ti-6Al-4V. They found that on average, chilled air and wet machining have produced the lowest surface roughness. With regards to the tool life, the authors concluded that cooled MQL with vegetable oil and cryogenic cooling are the most suitable sustainable alternatives for wet machining.

Cryogenic machining using liquefied gases has attracted considerable attention in recent years as an effective technique to improve the machinability of different materials, particularly difficult-to-machine alloys. Investigation of the published literature (Shokrani et al., 2013) concluded that the majority of studies in cryogenic machining have taken place after year 2000, with titanium alloys being the second most studied material after steel alloys. However, majority of these studies are concentrated on single point turning operations and there is a significant gap on milling operation. Furthermore, due to the intermittent nature of milling and particularly end milling with solid carbide tools, machinability benefits achieved by cryogenic cooling in single point turning operations cannot be extended to milling. For instance, whilst cryogenic cooling has been reported (Hong and Broomer, 2000, Kalyankumar and Choudhury, 2008, Khan and Ahmed, 2008, Khan et al., 2010) to significantly improve machinability of stainless steel, Nalbant and Yildiz (2011) and Muñoz-Escalona et al. (2015) reported that no significant improvements were achieved in cryogenic milling of AISI 304 and AISI 303 stainless steel, respectively in comparison with conventional machining environments.

The aim of this paper is to compare the effects of cryogenic cooling in end milling of Ti-6Al-4V alloy with dry and flood cooling and provide a significant benchmark for further studies in cryogenic machining. Therefore, in this paper, the effect of cryogenic cooling on various machinability metrics are compared with conventional machining environments, namely dry and flood cooling. The machinability metrics studied in this paper includes surface roughness, tool life, power consumption and specific machining energy.

METHODOLOGY FOR MACHINING EXPERIMENTS AND DATA COLLECTION

The detailed methodology used for this study is illustrated in figure 1.

Based on the findings in the literature and recommendations by Hong and Ding (2001), a cryogenic cooling system was retrofitted into a Bridgeport VMC 610 vertical CNC milling centre. As shown in figure 2, an external nozzle is designed which is placed around the cutting tool to spray LN_2 at -197°C along the cutting tool targeting the cutting zone thus, cooling the cutting tool and cutting zone simultaneously without submerging the workpiece in LN_2. The nozzle is designed to have 0.5mm clearance on each side from the cutting tool. The LN_2 is delivered at the point of cut at 1.5bar pressure and 0.4L/min flow rate. As illustrated in figure 3, the LN_2 is supplied from a cryogenic Dewar and delivered to the point of cut using a series of vacuum jacket pipes to minimise evaporation. As shown in figure 3, a 2/2 normally closed solenoid valve is used to turn the flow on and off which is connected to a bespoke electronic control system. For safety reasons and to prevent entrapment of LN_2 inside the vacuum jacketed pipes, a 3bar relief valve is positioned between the solenoid valve and the quick release coupling. The flow of LN_2 is monitored using a Coriolis flow meter.

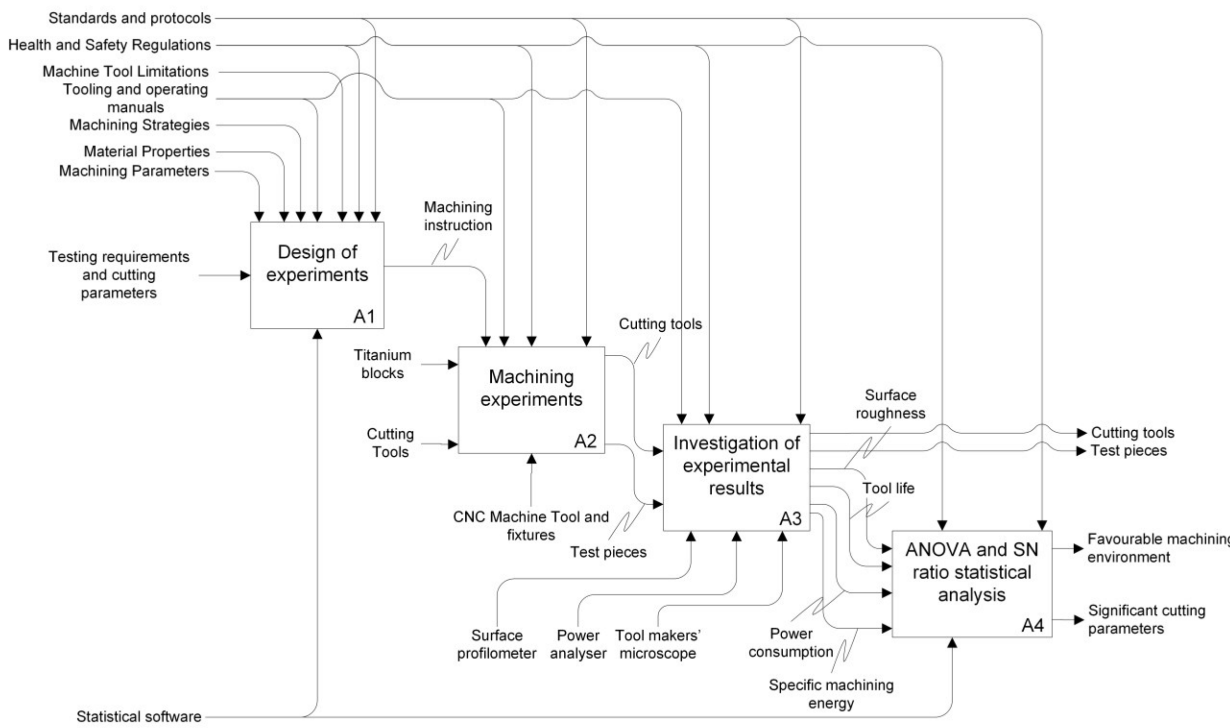


Figure 1, IDEF 0 representation of the methodology used for experimental investigation

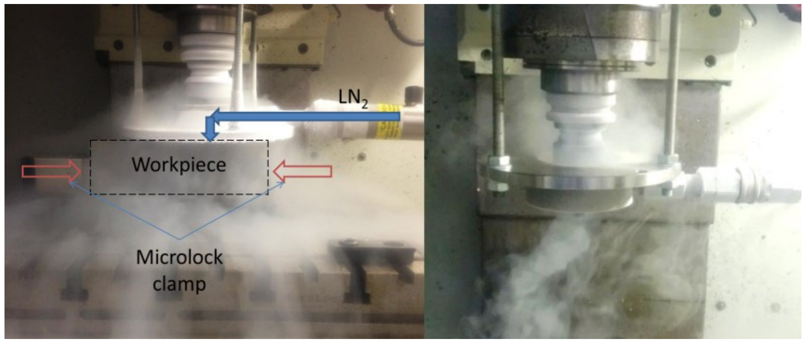


Figure 2, Cryogenic machining setup

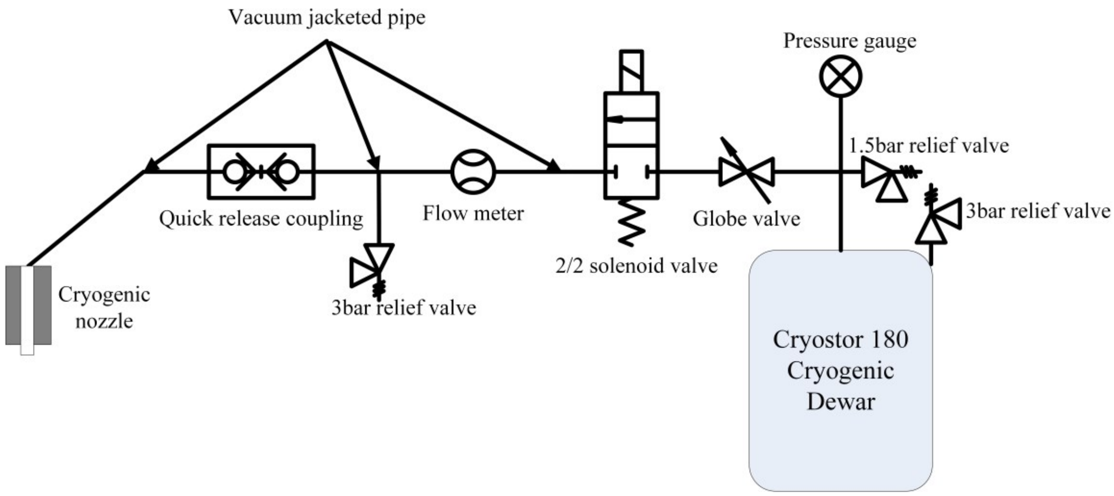


Figure 3, Schematic presentation of cryogenic cooling system

To investigate the effects of cryogenic cooling on the machinability of Ti-6Al-4V alloy, it is necessary to compare various machinability metrics such as surface roughness, tool life, power consumption and energy consumption per unit volume of machined material (specific machining energy) for different machining environments, namely dry, flood and cryogenic cooling. In order to develop a systematic method for experimentation and reduce the number of machining experiments, an L9 orthogonal array design of experiments (DoE) was used and repeated three times. Four machining parameters, namely cutting speed, feed rate, depth of cut and machining environment each at three levels were used for the DoE as shown in table 1. The upper and lower limits of the parameters were dictated by the limitations of the machine tool used for this study and/or the common practice suggested by tool manufacturers.

Table 1, experimental parameters and their corresponding levels

Symbol	**Parameter**	**Level**		
		Min	Mid	Max
V_c	Cutting speed (m/min)	30	115	200
f_z	Feed rate (mm/tooth)	0.03	0.065	0.1
a_p	Depth of cut (mm)	1	3	5
E	Machining environment	Dry	Cryogenic	Flood

An L9 orthogonal array design was identified for the experimental plan and four machinability metrics, namely surface finish (Ra), tool life, power consumption (P) and specific machining energy (SE) were selected for monitoring and analysis. In order to minimise the effects of random errors, each machining experiment was repeated three times and the average value was used for further analysis. Table 2 illustrates the DoE and the level of each parameter for each experiment. Based on this approach, if the signal-to-noise (SN) ratio identifies cryogenic cooling as the optimum level for the machining environment, it can be concluded that this approach has the potential to improve machinability of Ti-6Al-4V in comparison with conventional machining environments.

For each machining experiment, a 12mm diameter TiN-TiAlN coated solid carbide end mill with three flutes, 12° rake and 30° flute angle was used. The tool overhang and radial engagement were kept constant to 50mm and 33% respectively for all the experiments. The machining experiments were conducted on a 3-axis Bridgeport VMC 610XP vertical CNC milling centre which was equipped with a power demand analyser sampling at a rate of every 0.5sec.

Table 2, L9 orthogonal array design of experiments

Experiment ID	Cutting speed (V_c) m/min	Feed rate (f_z) mm/tooth	Depth of cut (a_p) mm	Machining environment (E)
1	30	0.03	1	Dry
2	30	0.065	3	Cryogenic
3	30	0.1	5	Flood
4	115	0.03	3	Flood
5	115	0.065	5	Dry
6	115	0.1	1	Cryogenic
7	200	0.03	5	Cryogenic
8	200	0.065	1	Flood
9	200	0.1	3	Dry

A block of annealed Ti-6Al-4V titanium alloy with the dimension of 150mmx100mmx50mm was prepared for each experiment and all the blocks were sourced together to minimise variability of material properties. As shown in figure 4, the experiment consisted of 150mm straight slot milling operations along the workpiece blocks until the cutting tool reached the tool life criterion as specified in ISO 8688-2 (1989). The tool travel with feed started 100mm before the workpiece and continued 100mm after the block to allow for acceleration and deceleration.

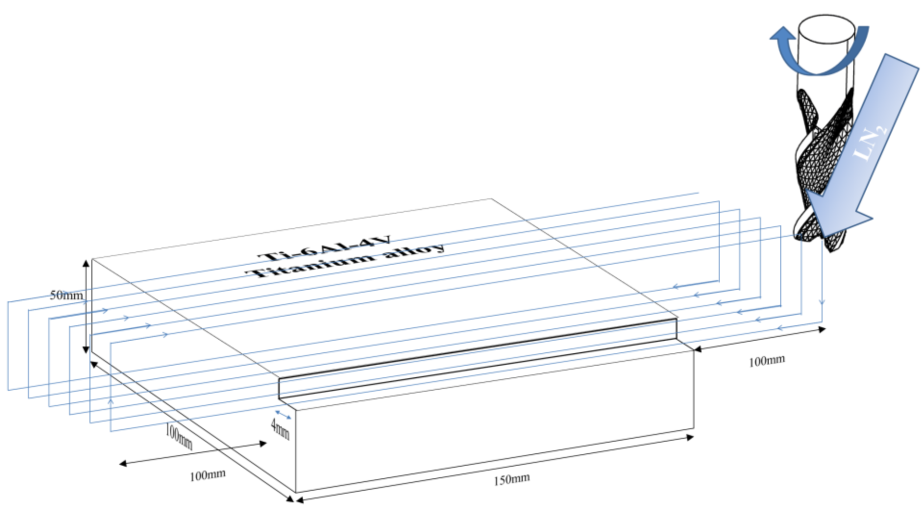


Figure 4, Pictorial view of the machining experiments

In order to minimise the effect of tool wear on surface roughness, the measurements were limited to the surface roughness of the first machining path as shown in figure 4. Figure 4 demonstrates an example tool path used for machining experiments. Surface roughness was examined according to BS EN ISO 4288 (1998) to provide meaningful and comparable results. A Proscan® 2000 3-D optical profilometer was used for measuring the arithmetic surface roughness (Ra) of the machined workpieces. Each machining sample was measured 5 times and the 20% truncated mean of the measurements was calculated to present the roughness of the machined surface.

The machining operation was interrupted at equal intervals and the tool wear was measured using a digital toolmaker's microscope. The ISO 8688-2 (1989) tool life testing in milling was considered to be the baseline for tool life. The end of tool life was defined as 300µm flank wear. All other tool wear phenomena e.g. chipping, flanking, etc. were treated as flank wear. The standard suggests presenting tool life in terms of machining time which is not representative of productivity. Therefore, the tool life was represented in terms of machining length (ML) and the volume of machined material (VMM).

The power consumption of the machine tool was monitored and recorded during the machining experiments. The average power consumption of the machine tool during the first machining path was calculated for each machining experiment. Specific machining energy was defined as the amount of energy used by machine tool to cut a unit volume of workpiece material. Hence, Eq. 1 was used to calculate the specific machining energy from the machine tool power consumption.

Eq. 1 $$SE = \frac{\int_0^t Pdt}{l \times a_p \times a_e}$$

where SE is specific machining energy in J/mm^3, t is material cutting time in *sec*, P is power consumption in *w*, l is machining length, a_p is axial depth of cut and a_e is radial depth of cut in mm.

EXPERIMENTAL RESULTS AND ANALYSIS

As explained by Ghani et al. (2004), using signal-to-noise (SN) ratio as a measure for process improvement , instead of standard deviation, is a more effective method for keeping the mean on target and reducing the standard deviation. According to Xin (2011), for this particular problem, the smaller-the-better and larger-the-better SN ratio were used as shown in equation 2 and 3 respectively.

- Smaller the better:

Eq. 2 $$SN = -10\log_{10}(\frac{\sum y^2}{n});$$

- Larger the better:

Eq. 3 $$SN = -10\log_{10}(\frac{1}{n}\sum\frac{1}{y^2});$$

where, n is the size of the population and y is the measured value for one test.

In order to improve general machinability characteristics, it is desired to minimise Ra, P and SE and thus the smaller-is-better SN ratio (Eq. 2) was favoured whilst the larger-is-better SN ratio (Eq. 3) was used for maximising the tool life (ML and VMM). Following machining experiments, various machinability metrics were collected and their corresponding SN ratios were calculated as presented in table 3.

Table 3, Experimental results for surface roughness (Ra), tool life (ML and VMM), power consumption (P) and energy consumption for unit volume of machined material (SE)

	Measured Values					Signal to Noise Ratio				
ID	Ra (µm)	ML (mm)	VMM (mm^3)	P (W)	SE (J/mm^3)	Ra (dB)	ML (dB)	VMM (dB)	P (dB)	SE (dB)
1	0.26	7200	28800	1290	268.9	11.6	77.2	89.2	-62.2	-48.6
2	0.50	4650	55800	1331	51.1	6.1	73.4	94.9	-62.5	-34.2
3	1.16	1050	21000	2164	27.4	-1.4	60.4	86.4	-66.7	-28.8
4	0.62	900	10800	1998	108.8	4.2	59.1	80.7	-66.0	-40.7
5	0.65	1950	39000	1574	10.5	3.8	65.8	91.8	-63.9	-20.7
6	0.68	1500	6000	1361	22.7	3.4	63.5	75.6	-62.7	-27.1
7	0.26	3000	60000	1479	28.1	11.8	69.5	95.6	-63.4	-29.0
8	0.67	1200	4800	2190	36.5	3.5	61.6	73.6	-66.8	-31.3
9	1.12	300	3600	2009	6.7	-1.0	49.5	71.1	-66.1	-16.6

As described by Xin (2011), the mean SN ratio of each level was calculated for each parameter and the largest SN ratio corresponds to the optimum level of a given parameter. Table 4 shows the mean SN ratio at different levels of each parameter for different machinability metrics with the highest SN value for each parameter highlighted.

Analysis of variance (ANOVA) was performed on the experimental results in order to identify the significance level and contribution percentage of each parameter on the desired machinability metric. Pareto ANOVA was used to visualise the compound effects of the input parameters. This method is used by researchers such as Ghani et al. (2004) and Palanikumar (2006) in order to identify the significance level and contribution of parameters on a desired output. The mean of the results at each level of the parameters was calculated and was used to compute the sum of squares (SS) for each parameter. Based on the SS, the contribution percentage of each parameter was calculated and accordingly each parameter was ranked based on its effect on the desired machinability metric. Pareto ANOVA graphs of the data for Ra, tool life (ML and VMM) and P were generated and are further discussed in the next section.

Table 4, Mean SN ratios for machining parameters at each level for different machinability metrics

Machinability Metric	Cutting Parameter	Mean of SN ratio (dB)		
		Min	Mid	Max
Surface roughness (Ra)	Cutting speed	5.5	3.8	4.8
	Feed rate	9.2	4.5	0.4
	Depth of cut	6.6	3.1	4.8
	Machining environment	4.8	7.1	2.1
Machining length (ML)	Cutting speed	70.3	62.8	60.2
	Feed rate	68.6	66.9	57.8
	Depth of cut	67.4	60.7	65.3
	Machining environment	64.2	68.8	60.4
Volume of machined material (VMM)	Cutting speed	90.2	82.7	80.1
	Feed rate	88.5	86.8	77.7
	Depth of cut	79.5	82.2	91.3
	Machining environment	84.1	88.7	80.3
Power consumption (P)	Cutting speed	-63.8	-64.2	-65.4
	Feed rate	-63.9	-64.4	-65.2
	Depth of cut	-63.9	-64.9	-64.7
	Machining environment	-64.1	-62.9	-66.5
Specific machining energy (SE)	Cutting speed	-37.17	-29.42	-25.58
	Feed rate	-39.43	-28.60	-24.13
	Depth of cut	-35.65	-30.47	-26.04
	Machining environment	-28.50	-30.08	-33.58

DISCUSSION

Signal to noise ratio analysis was used to analyse the experimental results. This technique suggests visual inspection of the mean SN ratio results as an interpretation method for analysing the results. Thus, it recommends plotting the mean SN ratios against each parameter's level for each parameter.

The largest SN ratio indicates the optimum level of that particular parameter for the desired machinability metrics as explained by Xin (2011). Therefore, the mean SN ratio plots were generated according to the calculations used for table 4. Based on the findings presented in table 4, cryogenic machining had demonstrated the highest mean SN ratio across majority of the machinability metrics studied. This indicated that cryogenic machining has the potential to improve surface roughness and tool life whilst reducing the power and energy consumption of the machine tool. In the following sections, the results obtained for each machinability metric are discussed.

Surface roughness

The analysis of mean SN ratio plots for surface roughness, as demonstrated in figure 5, indicated that cryogenic environment has the highest SN ratio as compared to dry and flood environments, thus has the potential to significantly improve surface roughness. Comparison of the means for machining environment reveals that on average 30% and 42% lower surface roughness were generated as compared to dry and flood machining respectively. This is in line with findings from Rotella et al. (2014) in turning of Ti-6Al-4V, where generation of improved surface roughness and surface integrity has been reported by using cryogenic cooling methods as opposed to dry and flood machining environments.

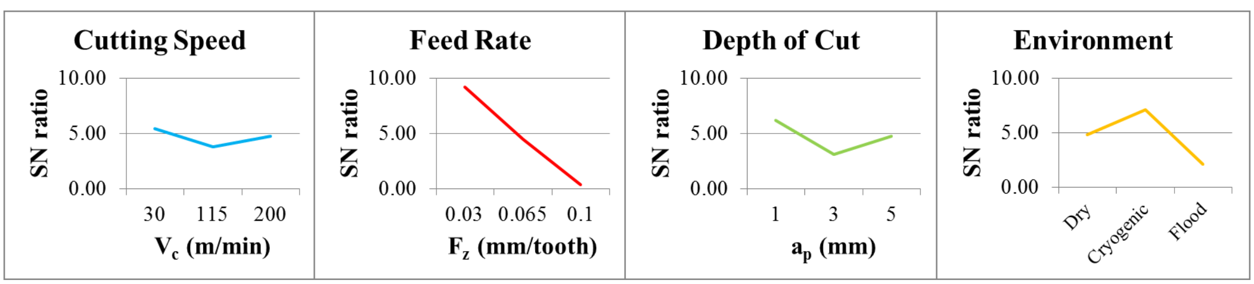
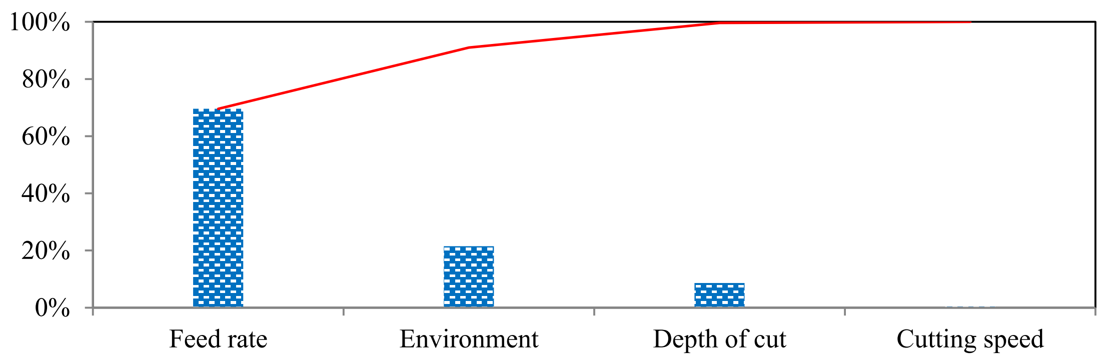


Figure 5, Main effects plots for mean SN ratio for surface roughness (Ra)

Pareto ANOVA of the experimental data for surface roughness, figure 6, demonstrated that machining environment is the second most significant parameter after feed rate to control surface roughness. Pareto ANOVA showed that, feed rate and machining environment form more than 90% of accumulated contribution in controlling surface roughness.

	Means of results			SS	Contribution%	Rank
	Min	Mid	Max			
Cutting speed	0.64	0.65	0.68	0.003	0.4%	4
Feed rate	0.38	0.60	0.99	0.568	69.5%	1
Depth of cut	0.54	0.75	0.69	0.07	8.6%	3
Environment	0.68	0.48	0.82	0.175	21.5%	2



Accumulative contribution	69.5%	91%	99.6%	100%

Figure 6, Pareto ANOVA of the experimental results for surface roughness (Ra)

The mean SN ratio graphs for surface roughness illustrated in figure 5, show that the highest SN ratios and thus the desired levels for machining parameters in order to minimise Ra are at the minimum level of cutting speed (30m/sec), feed rate (0.03mm/tooth) and depth of cut (1mm) using the cryogenic environment. Similar results can be interpreted from table 4 where the values of the SN ratios are presented and the highest levels are identified. Furthermore, Pareto ANOVA indicated that the most significant parameter affecting Ra is feed rate with 69.5% contribution followed by machining environment (21.5%) and depth of cut (8.6%).

Tool life

ISO 8688-2 (1989) recommends presenting tool life in terms of machining time. However, where machining time is affected by cutting speed and feed rate and the volume of machined material is affected by depth of cut, machining time fails to provide a meaningful measure for productivity. As explained in section 2, in this paper, two different measures, namely ML and VMM were used to represent tool life. The study of the SN ratio results provided in table 4 and their corresponding graphs for tool life (ML and VMM) shown in figures 5 and 6, revealed that with regards to machining environment, the cryogenic environment has the highest mean SN ratio as compared to dry and flood. Thus, it can be concluded that cryogenic machining is capable of improving tool life in machining Ti-6Al-4V alloy.

The analysis of mean SN ratio graphs for ML and VMM, as shown in figure 7 and 8 respectively, recommended using lower feed rate (0.03mm/tooth) and cutting speed (30m/min). The analysis indicated that lower depth of cut (1mm) is more favourable when the machining length is of interest whilst higher depths of cut (5mm) should be used to maximise VMM.

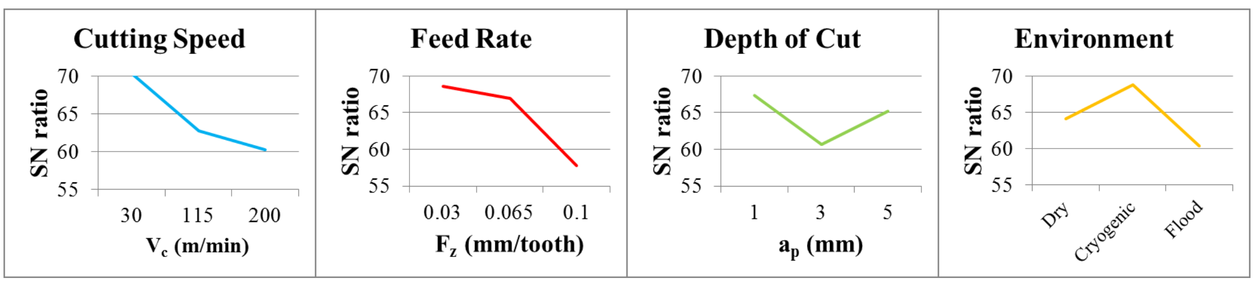


Figure 7, Main effects plots for mean SN ratio for tool life (ML)

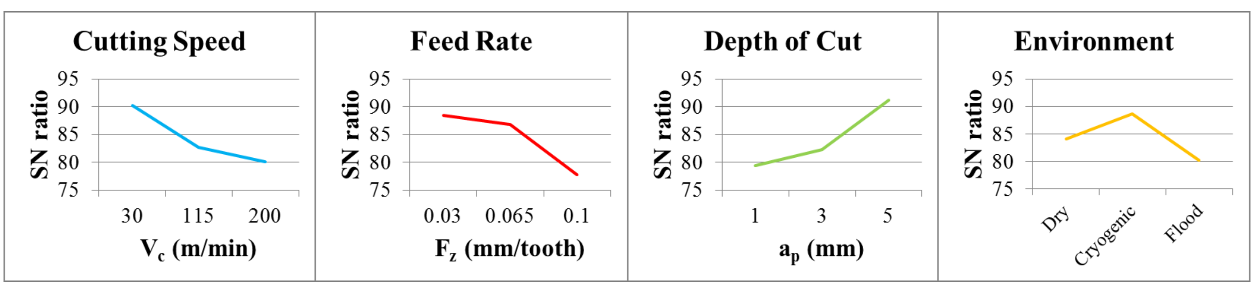
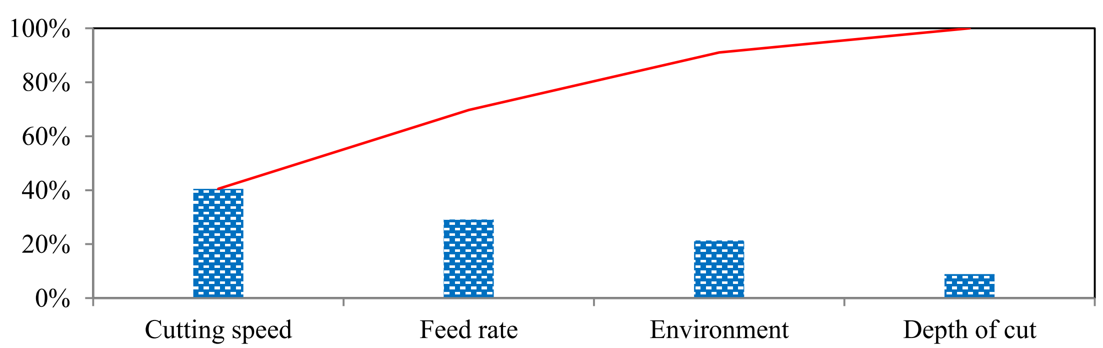


Figure 8, Main effects plots for mean SN ratio for tool life (VMM)

Analysis of the means for machining environment shows that whilst ML for cryogenic environment is only 3% more than dry, it is 190% more than ML for flood cooling. Furthermore, VMM is 70% and 230% more for cryogenic machining as compared to dry and flood, respectively. Pareto ANOVA of the experimental results obtained for ML (figure 9) illustrated that cutting speed (40.5%) and feed rate (29.2%) are the most significant parameters followed by machining environment (21.4%) and depth of cut (8.9%). For VMM (figure 10), the most significant parameters were identified to be machining environment (32%), depth of cut (28.7%), feed rate (27.7%) and cutting speed (11.7%) respectively. Due to the stochastic nature of the DoE used for this study, vis-à-vis comparison of the cutting tools at various cutting parameters is not possible. Thus, in this section the observations from experiments are reported individually.

The experimental results, presented in table 3, suggest that dry machining performs better at low cutting speeds and feed rates. At these conditions, where cutting temperature and forces are low, tool wear is predominantly abrasion and flaking of the coating. When the carbide substrate is exposed as a result of flaking and abrasion, the abrasive tool wear is accelerated and chipping, smearing and diffusion takes place. In contrast, at high cutting feeds and speeds, the wear is initiated by chipping and abrasion followed by adhesion and diffusion resulting in tool failure as shown in figure 11 for (a) experiment 8 and (b) experiment 9.

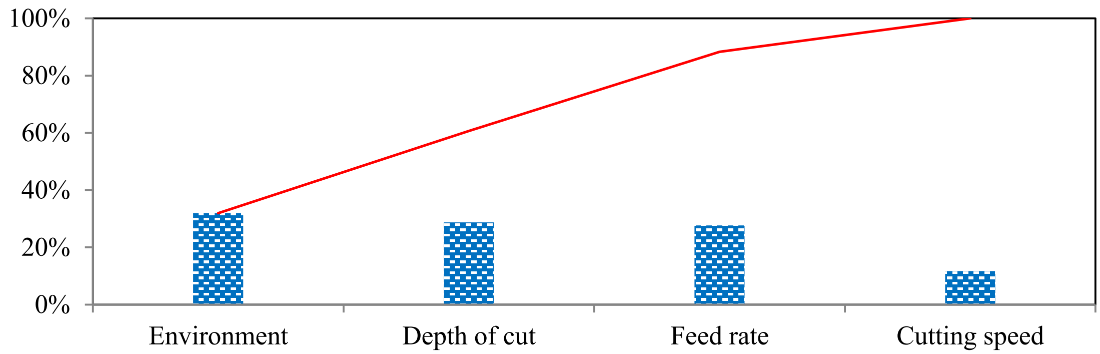
	Means of results			SS	Contribution%	Rank
	Min	Mid	Max			
Cutting speed	4300	1450	1500	15965000	40.5%	1
Feed rate	3700	2600	950	11495000	29.2%	2
Depth of cut	3300	1950	2000	3515000	8.9%	4
Environment	3150	3050	1050	8420000	21.4%	3



Accumulative contribution	40.5%	69.7%	91.1%	100%

Figure 9, Pareto ANOVA of the results for machining length (ML)

	Means of results			SS	Contribution%	Rank
	Min	Mid	Max			
Cutting speed	35200	18600	22800	446960000	11.7%	2
Feed rate	33200	33200	10200	1058000000	27.7%	3
Depth of cut	13200	23400	40000	1097840000	28.7%	4
Environment	23800	40600	12200	1223360000	31.0%	1



Accumulative contribution	31.0%	60.7%	88.3%	100%

Figure 10, Pareto ANOVA of the results for volume of machined material (VMM)

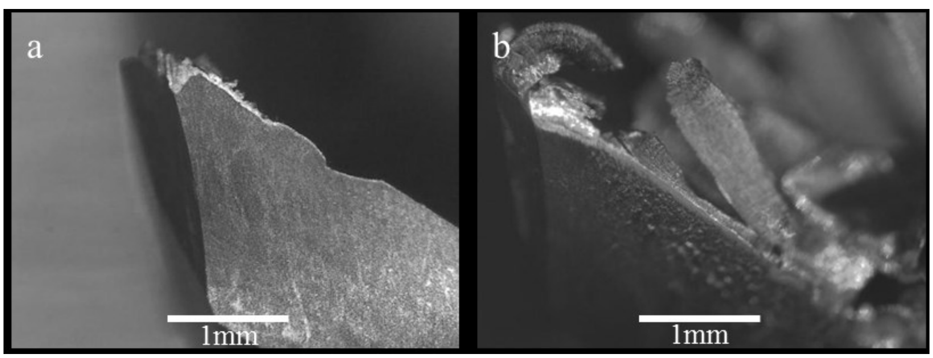


Figure 11, Chipping, abrasion, adhesion and diffusion wear as observed on the side of the cutting tools from (a) experiment 8 with 200m/min, 0.065mm/tooth, 1mm in flood environment and (b) experiment 9 with 200m/min, 0.1mm/tooth, 3mm in dry environment.

From the experiments, in all cases, the tool wear was initiated by mechanical wear such as abrasion and chipping and followed by thermal wear such as adhesion and diffusion. Through the sub-zero cooling effects of LN_2, the cryogenic environment has shown significant potential to decelerate thermally induced wear. For instance, as shown in figure 12 for experiment 7, abrasion wear has occurred after 8 machining passes (a) and chipping was observed as a result of crater wear after 12 passes (b). However, the 300μm flank wear threshold was reached after 20 passes with a uniform flank wear as shown in figure 12.c.

Crater wear was detected on all cutting tools irrespective of machining environment and cutting parameters, but the severity varied for each experiment. It has been observed that crater wear was more dominant at higher cutting speeds and feed rates which resulted in weakening of the cutting edge and chipping as shown in figure 13 taken from the tool used for experiment 5 in the flood environment. These observations are similar to those reported by Dhananchezian and Kumar (2011) in cryogenic turning. They reported that cryogenic cooling has reduced crater wear and lower flank wear was observed as compared to flood cooling.

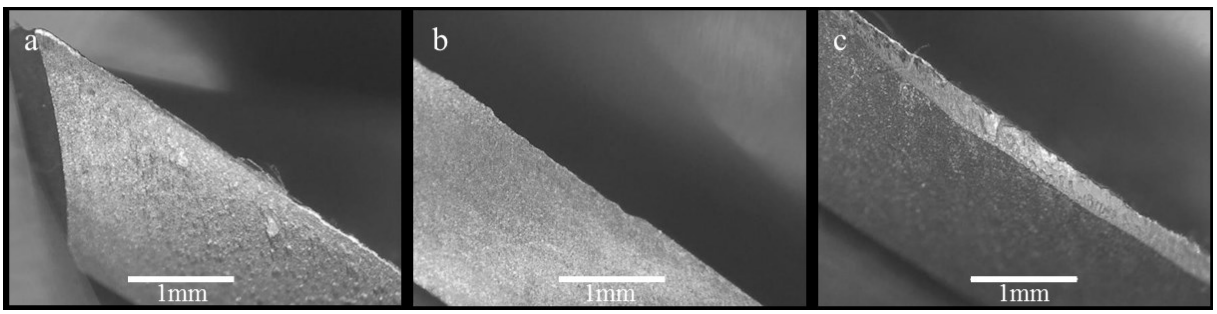


Figure 12, Microscopic images of the side of cutting tool used for experiment 7 at 200m/min, 0.03mm/tooth and 5mm in cryogenic environment after
(a) 8, (b) 12 and (c) 20 machining passes of 150mm.

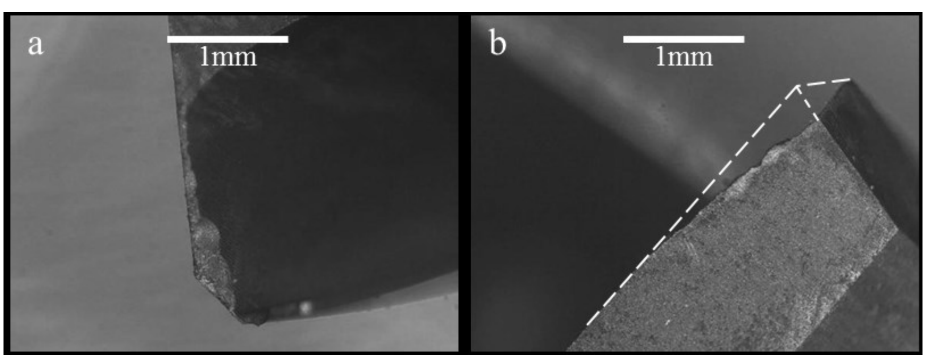


Figure 13, Microscopic images of (a) crater wear, flaking and (b) chipping of the cutting tool used for experiment 4 at 115m/min, 0.03mm/tooth and 3mm in flood cooling.

Power consumption and specific machining energy

Figure 14 illustrates an example graph of the power consumption against machining time for the first machining pass of experiment 1. As shown in the figure 14, the power consumption can be divided into 4 distinct sections of (i) idle, (ii) moving with feed without cutting material, (iii) moving with feed and cutting material and (iv) rapid move. To identify the power consumption for machining, the power consumption of the non-material cutting moves e.g. idle, feed without cutting and rapid move were removed from the analysis. Figure 15, demonstrate the power consumption graphs for all experiments during machining operation. From the results it can be observed that power consumption of the machine tool increases as the tool wear progress. However, the effect of tool wear on the total power consumption is not significant and in the case of high power demand processes at high cutting speed and feed rate is not noticeable. The effect is more distinct at lower cutting speed and feed rate such as experiment 1 where about 1% increase in the power consumption was recorded. This is mainly due to the significant power requirement for running the machine tool at idle state as compared to the power required at the tool tip for cutting material.

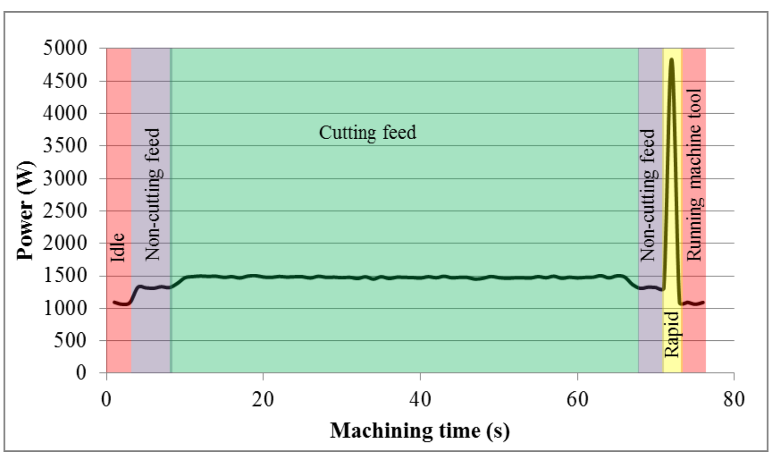


Figure 14, Power consumption graph for experiment 1

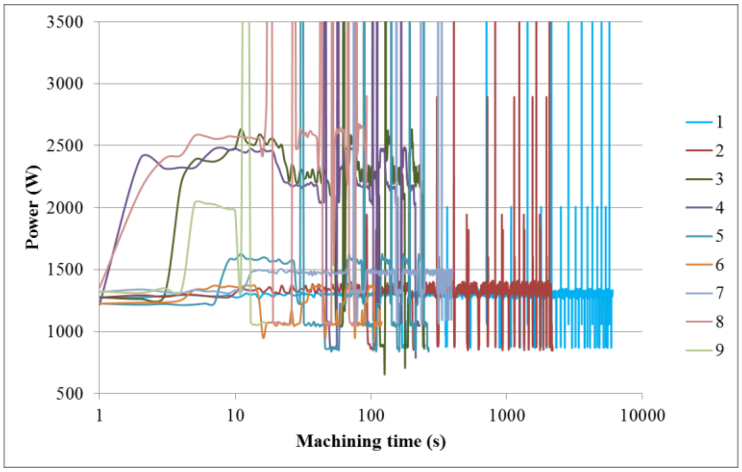


Figure 15, Power consumption of the machine tool for each experiment

The analysis of SN ratio (table 4) and visual examination of their corresponding graphs (figure 16) for power consumption recommends selecting the first level of cutting speed (30m/sec), feed rate (0.03mm/tooth) and depth of cut (1mm) using the cryogenic machining environment. Knowing that power consumption is a product of rotational velocity and torque, it is expected that lower cutting speed and feed rate require lower rotational speed of the machine tool's motors. However, although a lower depth of cut requires lower torque, there are other parameters such as friction, cutting temperature and material behaviour at various cutting temperatures which can affect the torque.

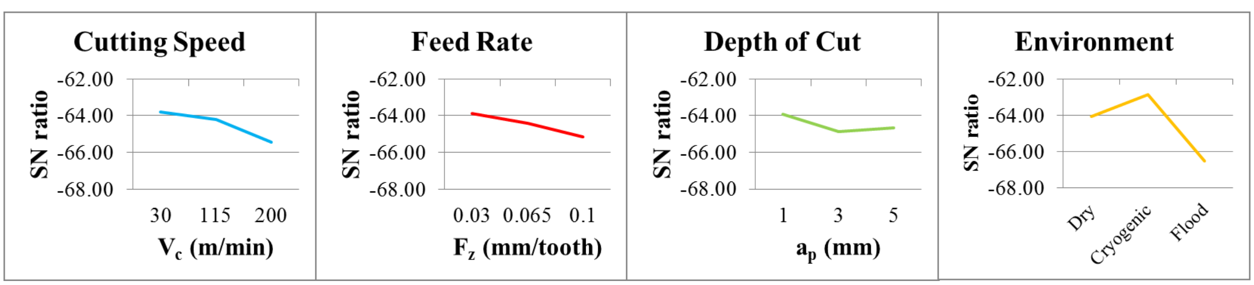
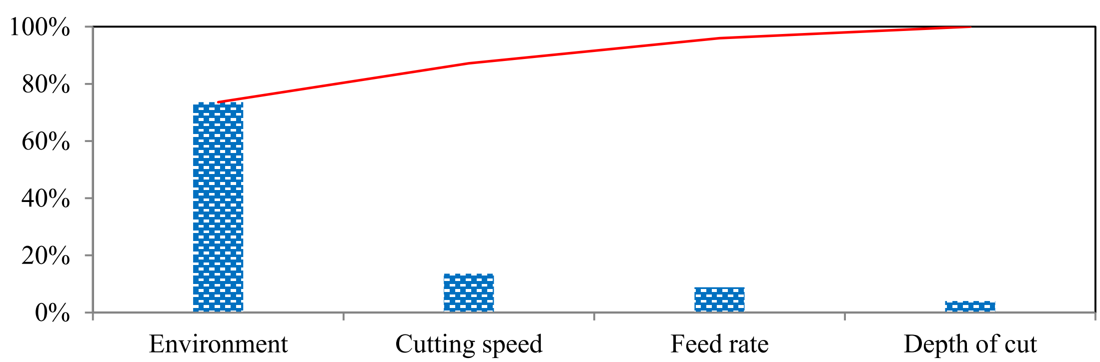


Figure 16, Main effects plots for mean SN ratio for power consumption (P)

With regards to the effect of machining environment on power consumption, it is clear that eliminating the coolant pump reduces the total machining power consumption. Consequently, both dry and cryogenic conditions are favourable over flood machining. This is supported by ANOVA of the results obtained for P (figure 17) showing that more than 73% of P is associated with the machining environment making it the most significant machining parameter. Cutting speed (13.6%) and feed rate (8.8%) were the next most significant parameters for power consumption which together with machining environment accounts for more than 96% accumulative contribution in P.

	Means of results			SS	Contribution%	Rank
	Min	Mid	Max			
Cutting speed	1596	1645	1893	152400	13.6%	2
Feed rate	1590	1699	1845	98795	8.8%	3
Depth of cut	1614	1780	1740	44794	4.0%	4
Environment	1625	1391	2118	826132	73.6%	1



Accumulative contribution	73.6%	87.2%	96.0%	100%

Figure 17, Pareto ANOVA of the results for P

Despite the recommendations for power consumption, the study of SN ratio for SE, as presented in table 4 and figure 18, suggested higher values of cutting speed, feed rate and depth of cut in order to achieve lower SE. As mentioned previously, energy is the integral of power with respect to time and therefore highly dependent on the total machining time. As the analysis of power consumption revealed, a significant portion of the power consumption is used for running the machine tool and not material cutting. Hence, extended machining time due to low material removal rates can significantly increase the amount of energy used for machining a unit volume of material. Consequently, higher material removal rates through using higher cutting speed, feed rate and depth of cut favourably reduces SE. This is in agreement with finding of Helu et al. (2012) that every effort should be made to increase material removal rate by increasing cutting speed and feed rate in order to minimise energy consumption for machining.

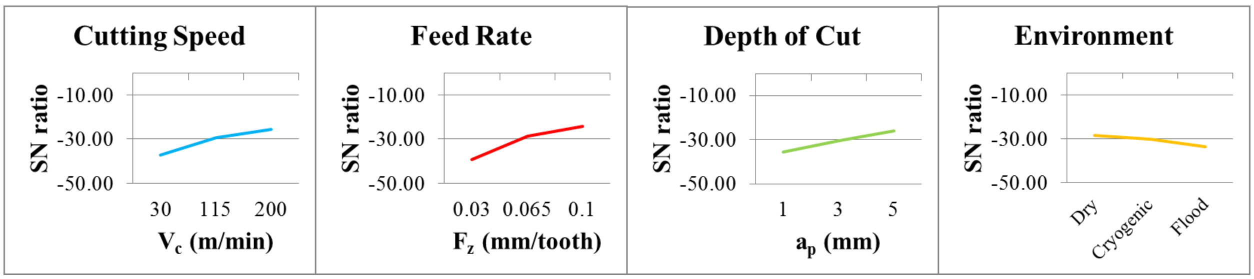
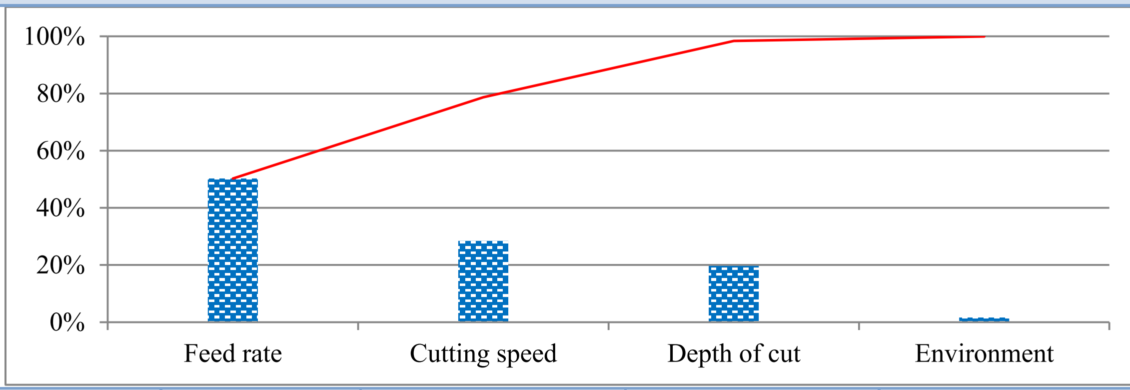


Figure 18, Main effects plots for mean SN ratio for specific machining energy (SE)

The power consumption of the coolant pump (800w) was deducted from the power consumption of the machine tool during flood cooling experiments and the specific machining energy (SE) was calculated using Eq. 1. The Grubb's test was performed and the outliers were trimmed to normalise the data. As shown in figure 19, the analysis indicated that feed rate (50%) and cutting speed (28%) are the most significant parameters affecting SE. The effect of machining environment on SE was identified to be minimal and statistically insignificant.

	Means of results			SS	Contribution%	Rank
	Min	Mid	Max			
Cutting speed	60.1	32.8	19.3	2586.17	28.4%	2
Feed rate	68.4	28.2	15.5	4572.32	50.3%	1
Depth of cut	52.6	41.0	18.6	1791.14	19.7%	3
Environment	43.0	33.9	35.2	145.06	1.6%	4



Accumulative contribution	50.3%	78.7%	98.4%	100%

Figure 19, Pareto ANOVA of the results for SE after removing the coolant pump's power consumption

CONCLUSION AND FURTHER WORKS

This paper has presented an investigation to identify the feasibility of cryogenic cooling using LN_2 in end milling Ti-6Al-4V titanium alloy as compared to conventional dry and flood cooling. From the investigations reported in this paper, following conclusions are drawn:

- Analysis of mean SN ratio graphs, presented in figure 5, 6, 7, 13 and 15, revealed that the most appropriate machining environment for improving machinability is the cryogenic environment. In other words, analysis of SN ratio identified the cryogenic environment as the optimum machining environment for optimising all machinability metrics investigated in this paper.
- The analysis showed that on average, cryogenic machining can reduce surface roughness (Ra) by 30% and 40% respectively in comparison with dry and flood environments.

- Machining experiments revealed that extremely low temperatures in cryogenic cooling reduces chemical reactivity between workpiece and cutting tool materials and decelerates thermally induced tool wear resulting in up to 3 fold increased tool life as compared to flood cooling.
- It was identified that a substantial portion of machine tool's power consumption is due to the coolant pump. Thus, cryogenic and dry environments are favourable to reduce power consumption and specific machining energy.
- Experimental machining tests and statistical analysis of the results indicated that cryogenic cooling has significant potential to make a paradigm change in machining of titanium alloys through improved machinability by producing lower surface roughness (Ra), extended tool life and lower power consumption and specific machining energy.

This study has clearly demonstrated the advantages of cryogenic machining as an emerging machining technique. In addition, further research is necessary to provide an in-depth understanding of the effects of cryogenic machining on material and mechanical properties of the Ti-6Al-4V workpiece.

NOMENCLATURE

a_e	Radial depth of cut
ANOVA	Analysis of variance
a_p	Axial depth of cut
DoE	Design of experiments
E	Machining environment
F_z	Feed rate
LN_2	Liquid nitrogen
ML	Machining length
P	Power
Ra	Arthmetic surface roughness
SE	Specific machining energy

SN ratio	Signal-to-noise ratio
SS	Sum of squares
t	Machining time
V_c	Cutting speed
VMM	Volume of machined material

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